A Software-Defined Radio Transmitter for Variable-Coded Modulation on a CubeSat

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Abstract:

The large volume of satellites sharing the same spectrum and the complexities of communications in Low-Earth Orbit (LEO) pose challenges to the downlink of large volumes of data on a platform that is bandwidth, power, and time limited. LEO satellites operate in a highly variable communications environment due to variations in inter-satellite or satellite-to-ground geometries, weather, and interference. Therefore, there is motivation for implementing satellite communication techniques that manage these issues to increase the data throughput. One such technique is variable-coded modulation which shows improvement by taking advantage of the dynamic nature of a satellite link. As part of the Air Force Research Laboratory University Nanosatellite Program, and in collaboration with NASA, this project focuses on the development of an S-band software defined radio for CubeSats that utilizes variable-coded modulation defined by the Digital Video Broadcasting-Satellite-Second Generation standard. This project defense discusses the initial development and testing using GNU Radio, and the challenges for full implementation, as well as the current status of the transmitter, and future work.

A Software Defined Radio Transmitter for Variable-Coded Modulation on a CubeSat

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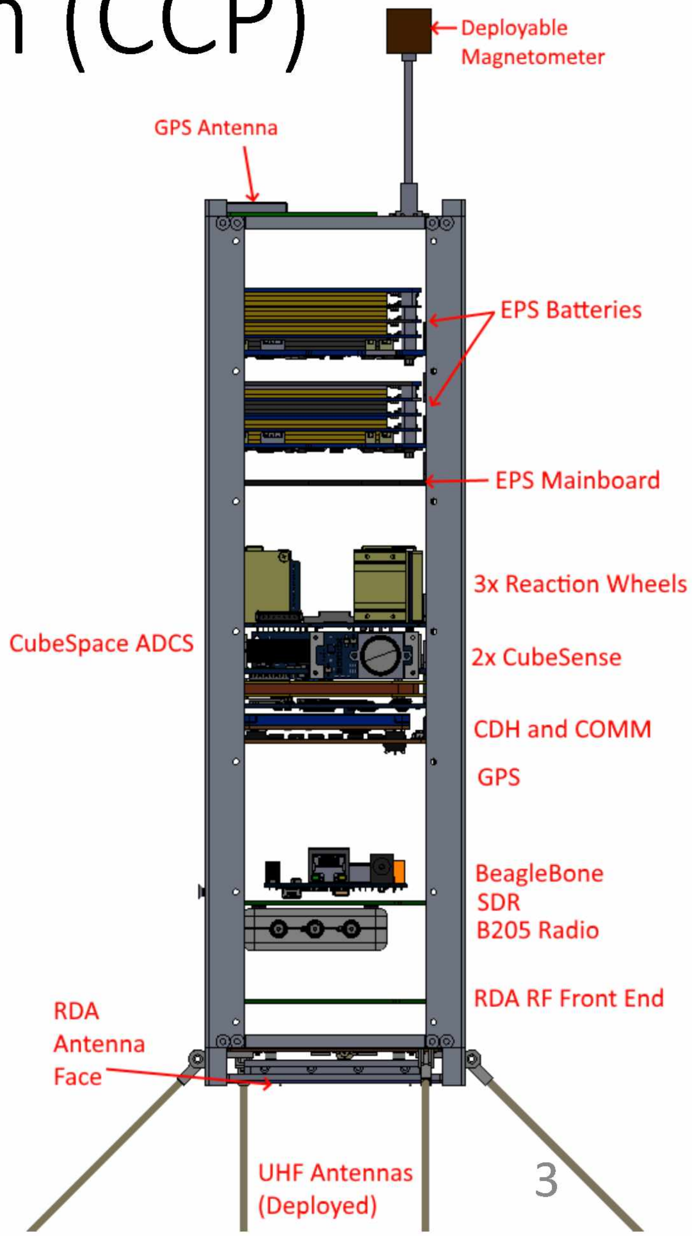
Outline

- CubeSat Communications Platform (CCP)
  - Link analysis
  - Variable-coded modulation
- Software Defined Radio (SDR)
  - Signal path
  - DVB-S2
- Initial SDR Development Approach
- Testing
  - Issues with initial approach
- Current Status and Next Steps

CubeSat Communications Platform (CCP)

- Air Force Research Labs (AFRL) – University Nano-Satellite Program (UNP)
- CCP Mission Objectives
  1. Characterize the on-orbit beam pointing error, power efficiency, and thermal load of the high-gain antenna payload. (Retrodirective Antenna)
  2. Characterize the on-orbit performance of the variable coded modulation payload with respect to the information throughput capabilities. (Software Defined Radio)
- Collaboration: NASA Near Earth Network (NEN)
- SpaceOps 2020 Conference Paper



CCP Link Analysis

General RF Parameters

Carrier Frequency
- S-Band
- 2.2 GHz

Bandwidth
- 5 MHz

Ground Station

Antenna Size
- NEN: 11 m
- UAF: 1.2 m

G/T
- NEN: 19 dB/K
- UAF: 6 dB/K

Symbol Rate
- NEN: 3.7 M Sym/s
- UAF: 3.7 M Sym/s

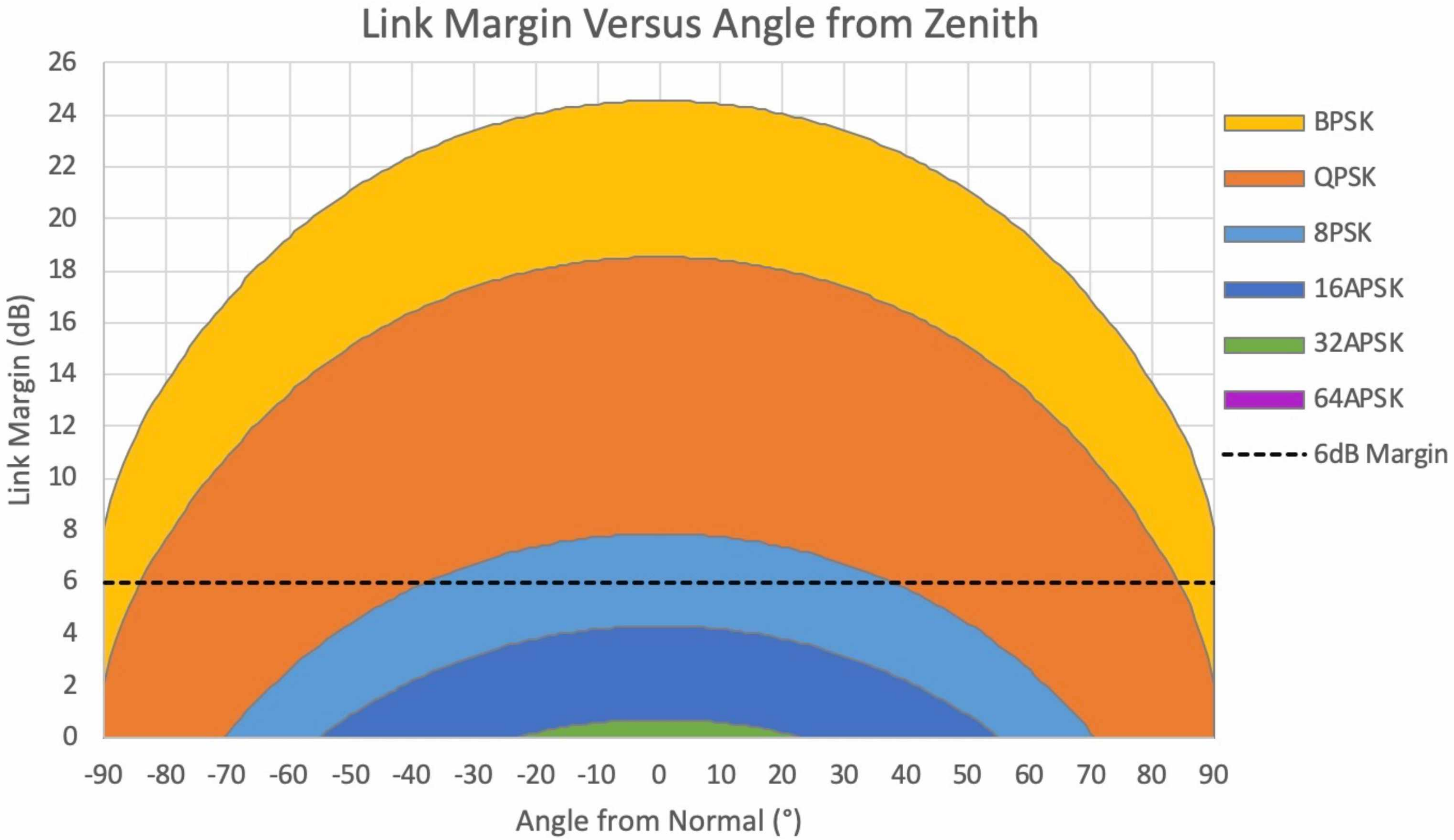
Spacecraft

Transmit Power
- 0 dBW

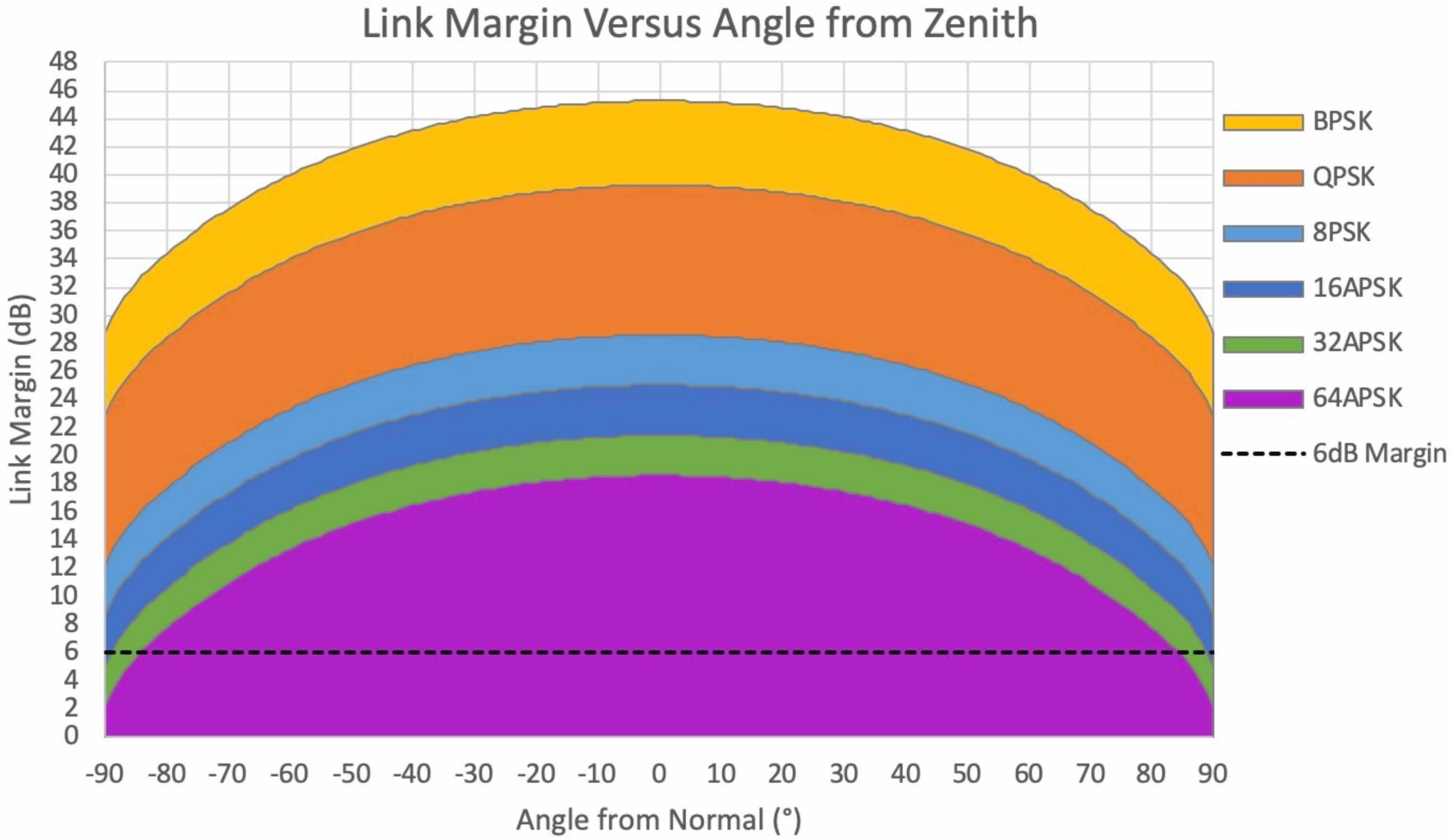
Antenna Gain
- 6 dB

EIRP
- 5.5 dBW

UAF Student Ground Station

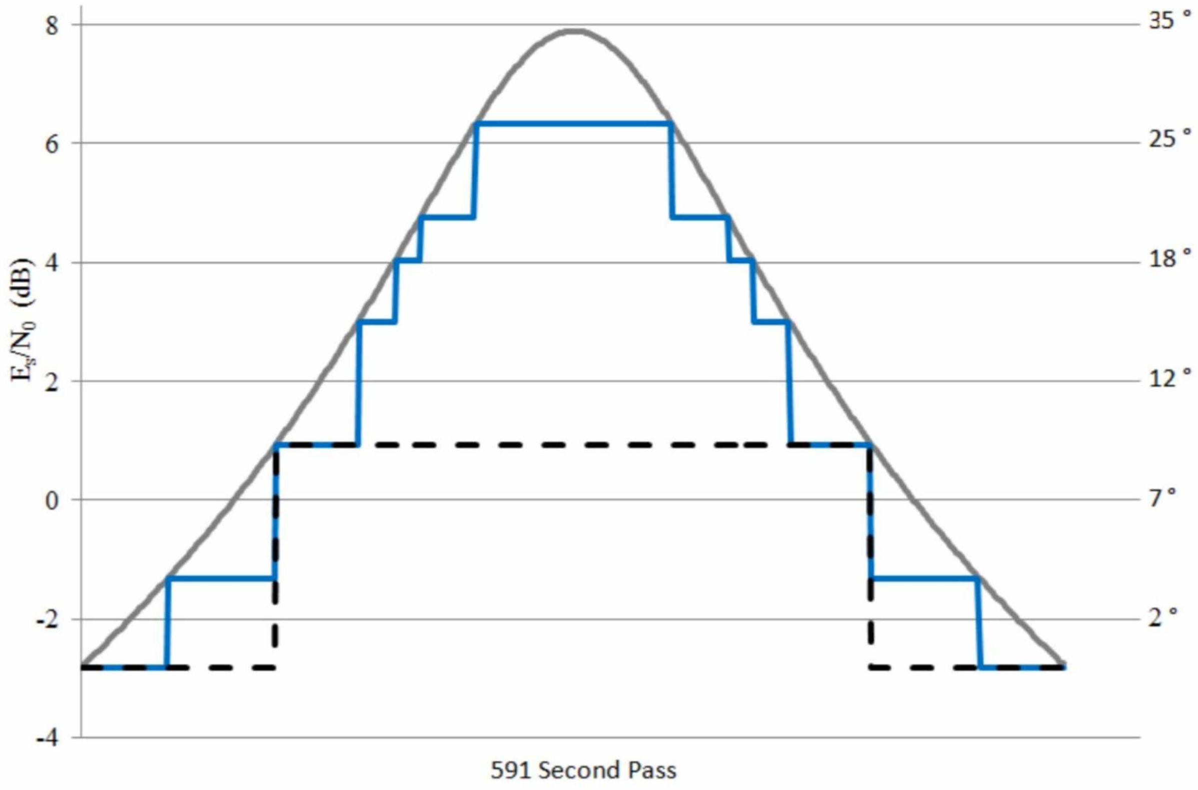


NASA Wallops Ground Station



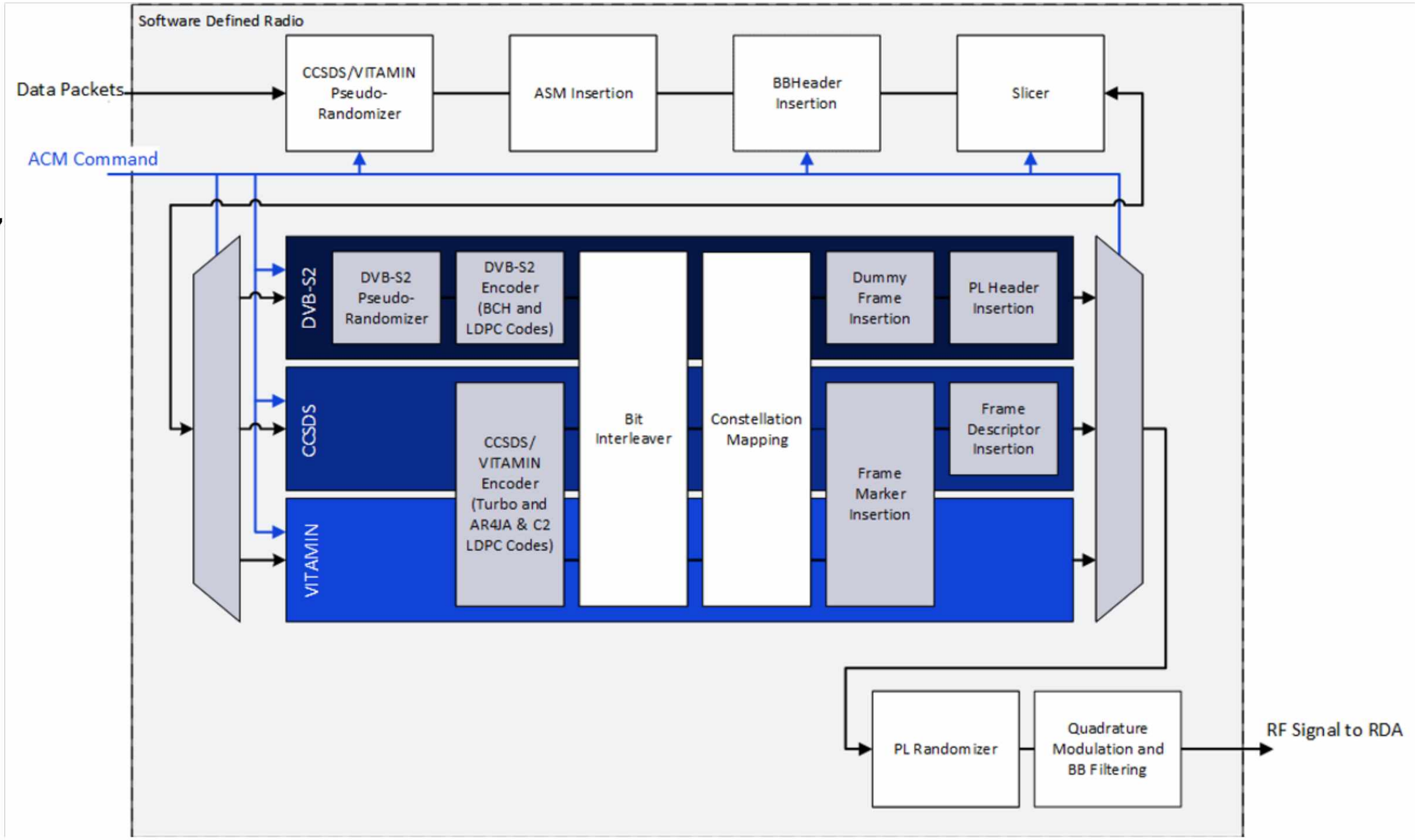
Variable-Coded Modulation (VCM)

- Variable link conditions
  - Distance from satellite to ground station
  - Weather
- Constant coding and Modulation (CCM)
  - Plans for “worst-case”
- Variable coded modulation (VCM)
  - Takes advantage of better conditions

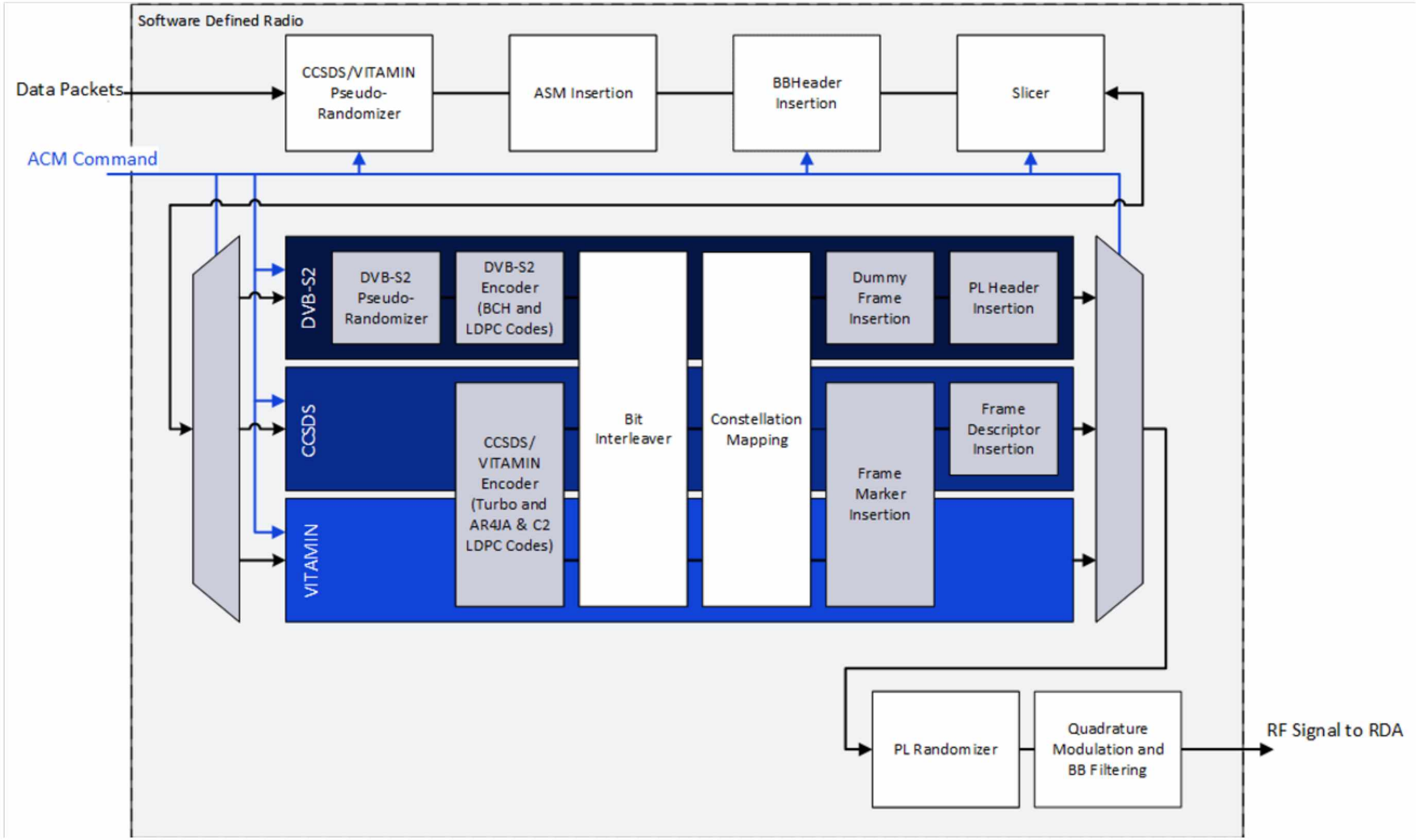


CCP – Software Defined Radio (SDR)

- Three protocols
  - DVB-S2, CCSDS, VITAMIN
- DVB-S2:
  - QPSK: 1/4, 1/3, 2/5, 1/2, 3/5, 2/3, 3/4, 4/5, 5/6, 8/9, 9/10
  - 8PSK: 3/5, 2/3, 3/4, 5/6, 8/9, 9/10
  - 16APSK: 2/3, 3/4, 4/5, 5/6, 8/9, 9/10
- CCSDS/VITAMIN:
  - BPSK: 1/6, 1/4
  - QPSK:
    - Turbo: 1/6, 1/4, 1/3, 1/2
    - AR4JA LDPC: 1/2 , 2/3, 4/5
    - C2 LDPC: 7/8
  - 8PSK:
    - AR4JA LDPC: 1/2, 4/5
    - C2 LDPC: 7/8
  - 16APSK:
    - AR4JA LDPC: 1/2, 2/3, 4/5, 7/8

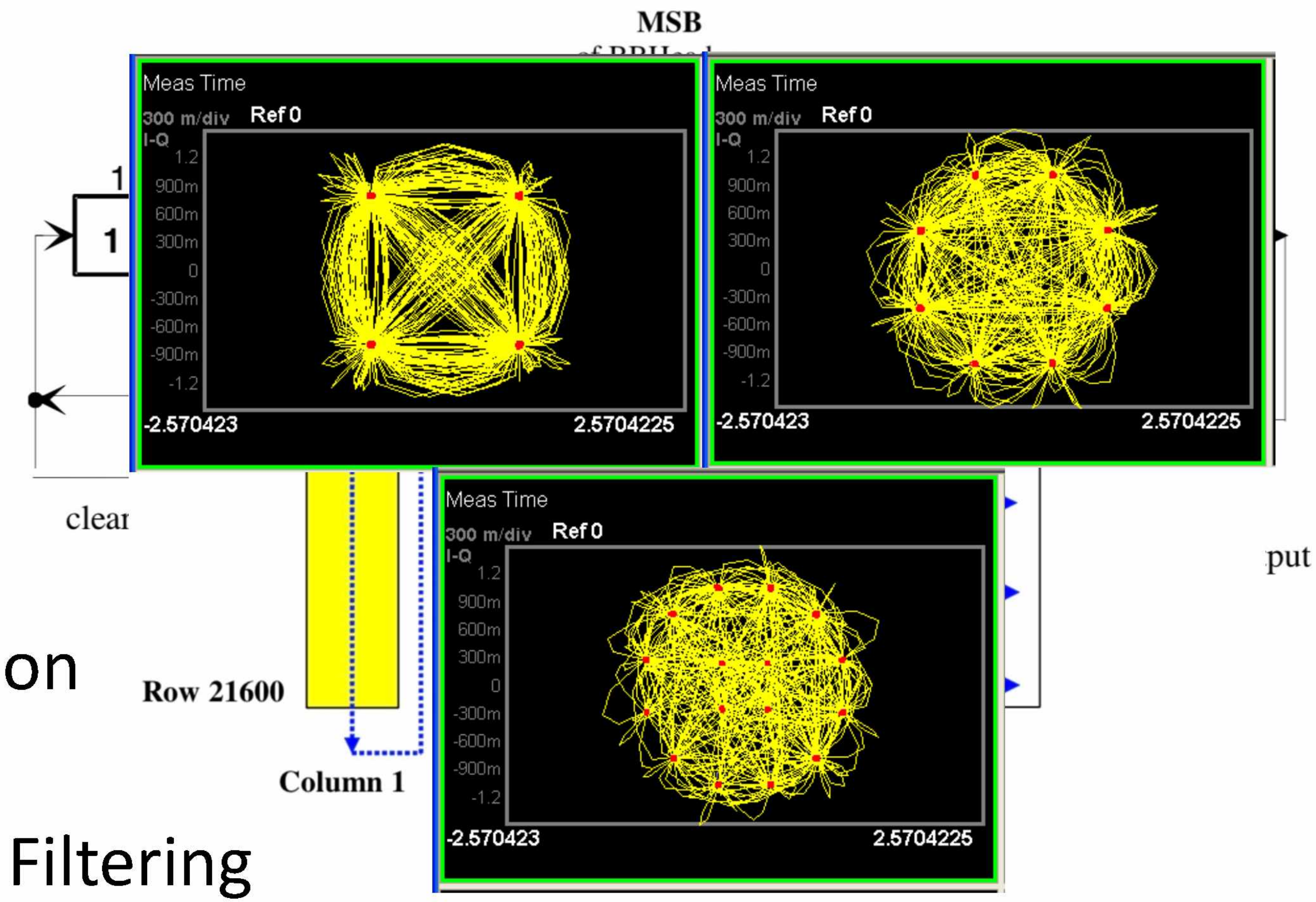


SDR Signal Path



DVB-S2 Functional Blocks

- Baseband header insertion
- Baseband scrambler
- Outer BCH Coding
- Inner LDPC Coding
- Bit Interleaver
- Constellation Mapping
- Physical Layer Header Insertion
- Physical Layer Randomizer
- Quadrature Modulation and Filtering



DVB-S2 Outer Encoding—BCH

- Bose-Chaudhuri-Hocquenghem (BCH) Code
- Simplified example encoding :
  - Message: 1011
  - Generator polynomial: $\mathrm{g(X)} = 1 + X^2$
  - Procedure
    - Message polynomial: $m(X) = 1 + X^2 + X^3$
    - Multiply message by X^2: $X^2 m(X) = X^2 + X^4 + X^5$
    - Divide by $g(X)$, the remainder is $p(X)$
    - The codeword polynomial is: $p(X) + X^2 m(X)$
      $0 + X + X^2 + 0X^3 + X^4 + X^5$
    - Coded bits: 011011

$$
\begin{array}{r l}
 & X^3 + X^2 + X \\
\cline{2-2}
1 + X^2 & \big) \; X^5 + X^4 + 0X^3 + X^2 + 0X + 0 \\
 & -(\mathrm{X}^5 + 0\mathrm{X}^4 + \mathrm{X}^3) \\
\cline{2-2}
 & \qquad \mathrm{X}^4 + \mathrm{X}^3 + \mathrm{X}^2 \\
 & \qquad -(\mathrm{X}^4 + 0\mathrm{X}^3 + \mathrm{X}^2) \\
\cline{2-2}
 & \qquad \qquad \mathrm{X}^3 \\
 & \qquad \qquad -(\mathrm{X}^3 + 0\mathrm{X}^2 + \mathrm{X}) \\
\cline{2-2}
 & \qquad \qquad \qquad X
\end{array}
$$

DVB-S2 Outer Encoding—BCH

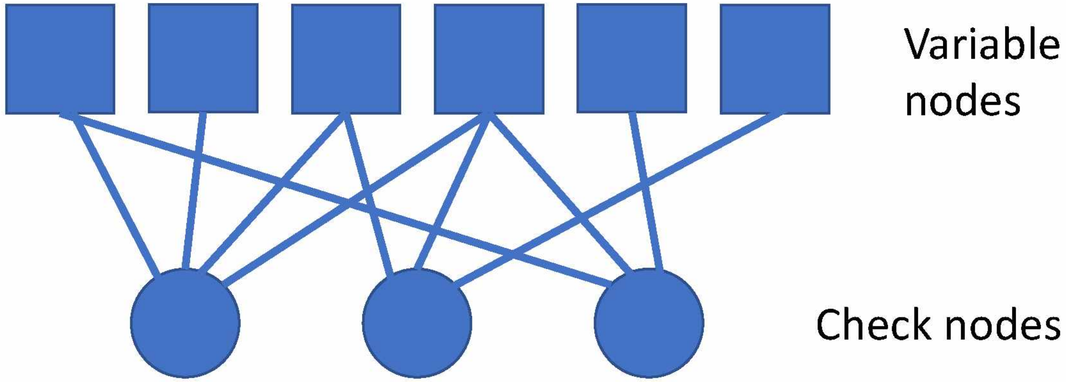
- More complex than the example
- DVB-S2 uses a generator polynomials of degree 128, 160, or 192
- Depending on LDPC code rate, can correct 8, 10, or 12 code bit errors
- Example: For an LDPC code rate of 1/4 → $(n, k) = (16200, 16008)$

$g_1(x)$	$1+x^2+x^3+x^5+x^{16}$
$g_2(x)$	$1+x+x^4+x^5+x^6+x^8+x^{16}$
$g_3(x)$	$1+x^2+x^3+x^4+x^5+x^7+x^8+x^9+x^{10}+x^{11}+x^{16}$
$g_4(x)$	$1+x^2+x^4+x^6+x^9+x^{11}+x^{12}+x^{14}+x^{16}$
$g_5(x)$	$1+x+x^2+x^3+x^5+x^8+x^9+x^{10}+x^{11}+x^{12}+x^{16}$
$g_6(x)$	$1+x^2+x^4+x^5+x^7+x^8+x^9+x^{10}+x^{12}+x^{13}+x^{14}+x^{15}+x^{16}$
$g_7(x)$	$1+x^2+x^5+x^6+x^8+x^9+x^{10}+x^{11}+x^{13}+x^{15}+x^{16}$
$g_8(x)$	$1+x+x^2+x^5+x^6+x^8+x^9+x^{12}+x^{13}+x^{14}+x^{16}$
$g_9(x)$	$1+x^5+x^7+x^9+x^{10}+x^{11}+x^{16}$
$g_{10}(x)$	$1+x+x^2+x^5+x^7+x^8+x^{10}+x^{12}+x^{13}+x^{14}+x^{16}$
$g_{11}(x)$	$1+x^2+x^3+x^5+x^9+x^{11}+x^{12}+x^{13}+x^{16}$
$g_{12}(x)$	$1+x+x^5+x^6+x^7+x^9+x^{11}+x^{12}+x^{16}$

BCH polynomials

DVB-S2 Inner Encoding—Low-Density Parity Check (LDPC)

A simple example:



$$\mathbf{H} = \begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 1 & 0 \end{bmatrix}$$

Parity check matrix

$$\mathbf{H} = \begin{bmatrix} 1 & 0 & 0 & 1 & 1 & 1 \\ 0 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 & 0 \end{bmatrix} = [\mathbf{I}_{n-k} \mid \mathbf{P}^{\mathrm{T}}]$$

$$\mathbf{G} = \begin{bmatrix} 1 & 0 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 0 & 1 \end{bmatrix} = [\mathbf{P} \mid \mathbf{I}_k]$$

$$\mathbf{U} = \mathbf{mG} = \begin{bmatrix} 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 1 & 1 & 0 & 1 \end{bmatrix}$$

DVB-S2 Inner Encoding—LDPC Encoding

- Normal baseband frame sizes are 64800 bits (value of n)
- For 1/4 rate →

$$(n, k) = (64800, 16200)$$

1. Accumulate information bit i_0 at parity bit addresses in row 1
2. Repeat for i_m where $m = 1, 2, \dots 359$ for parity address $(x + m \bmod 360 \times q) \bmod (n - k)$
3. Repeat for the next group of 360 using row 2
4. Repeat until all information bits are exhausted
5. Final parity follows: $p_i = p_i \oplus p_{i-1}$
6. The codeword, $\boldsymbol{c} = (i_0, i_1, \dots, p_{n-k}, p_{n-k-1})$

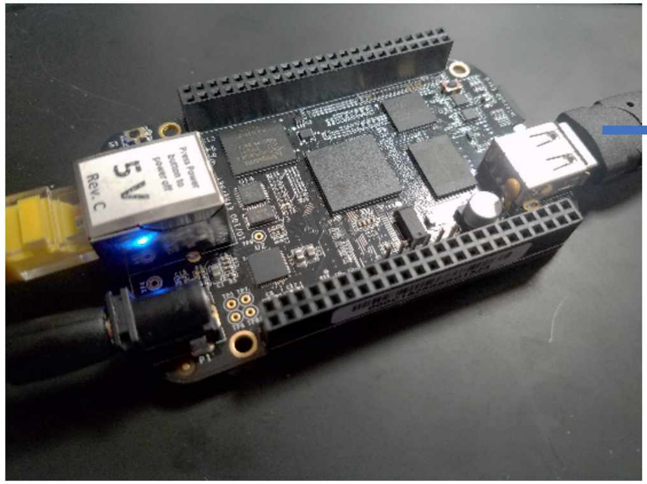
23606 36098 1140 28859 18148 18510 6226 540 42014 20879 23802 47088
16419 24928 16609 17248 7693 24997 42587 16858 34921 21042 37024 20692
1874 40094 18704 14474 14004 11519 13106 28826 38669 22363 30255 31105
22254 40564 22645 22532 6134 9176 39998 23892 8937 15608 16854 31009
8037 40401 13550 19526 41902 28782 13304 32796 24679 27140 45980 10021
40540 44498 13911 22435 32701 18405 39929 25521 12497 9851 39223 34823
15233 45333 5041 44979 45710 42150 19416 1892 23121 15860 8832 10308
10468 44296 3611 1480 37581 32254 13817 6883 32892 40258 46538 11940
6705 21634 28150 43757 895 6547 20970 28914 30117 25736 41734 11392
22002 5739 27210 27828 34192 37992 10915 6998 3824 42130 4494 35739
8515 1191 13642 30950 25943 12673 16726 34261 31828 3340 8747 39225
18979 17058 43130 4246 4793 44030 19454 29511 47929 15174 24333 19354
16694 8381 29642 46516 32224 26344 9405 18292 12437 27316 35466 41992
15642 5871 46489 26723 23396 7257 8974 3156 37420 44823 35423 13541
42858 32008 41282 38773 26570 2702 27260 46974 1469 20887 27426 38553
22152 24261 8297
19347 9978 27802
34991 6354 33561
29782 30875 29523
9278 48512 14349
38061 4165 43878
8548 33172 34410
22535 28811 23950
20439 4027 24186
38618 8187 30947
35538 43880 21459
7091 45616 15063
5505 9315 21908
36046 32914 11836
7304 39782 33721
16905 29962 12980
11171 23709 22460
34541 9937 44500
14035 47316 8815
15057 45482 24461
30518 36877 879
7583 13364 24332
448 27056 4682
12083 31378 21670
1159 18031 2221
17028 38715 9350
17343 24530 29574
46128 31039 32818
20373 36967 18345
46685 20622 32806

For 1/4 rate

Code Rate	q
1/4	135
1/3	120
2/5	108
1/2	90
3/5	72
2/3	60
3/4	45
4/5	36
5/6	30
8/9	20
9/10	18

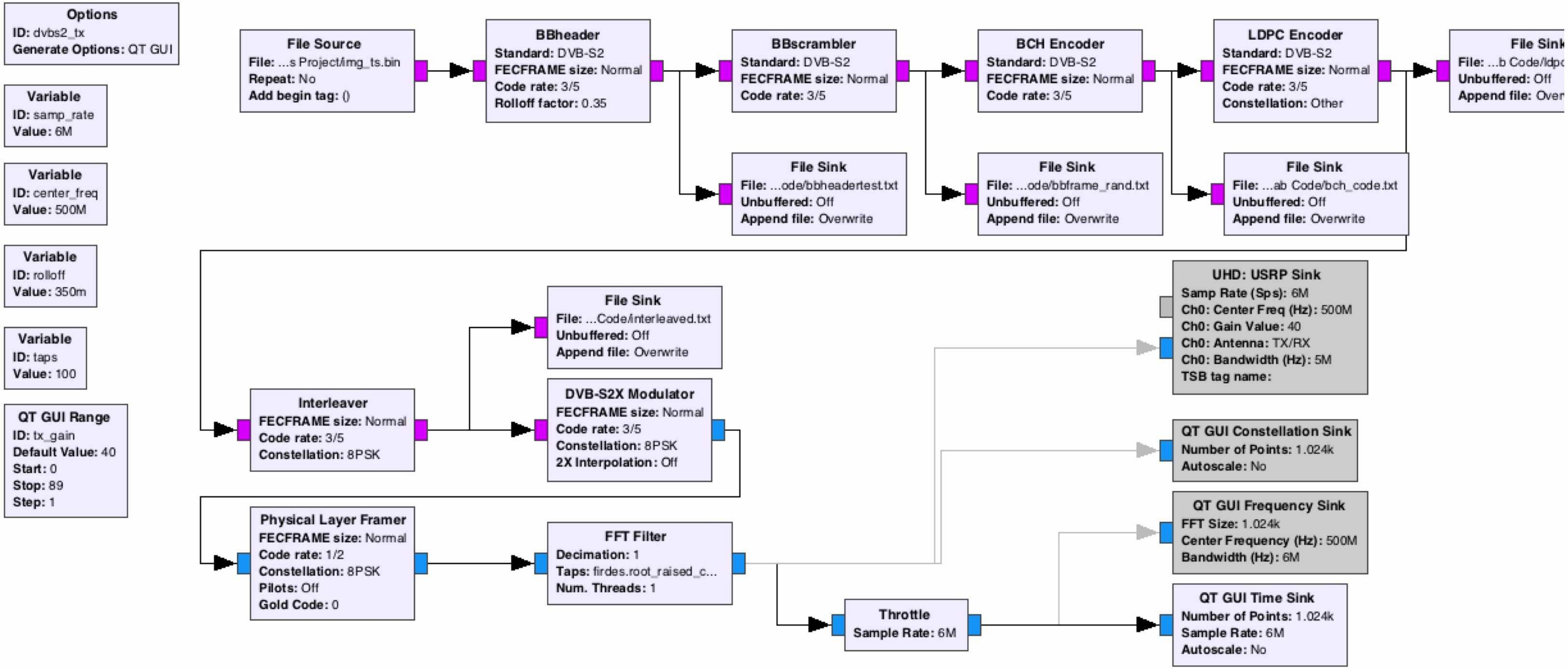
Initial SDR Development

- Started with DVB-S2
- NASA Near-Earth Network (NEN) partnership
- Initial approach
  - GNU Radio
  - B205 mini-I
  - Beaglebone Black



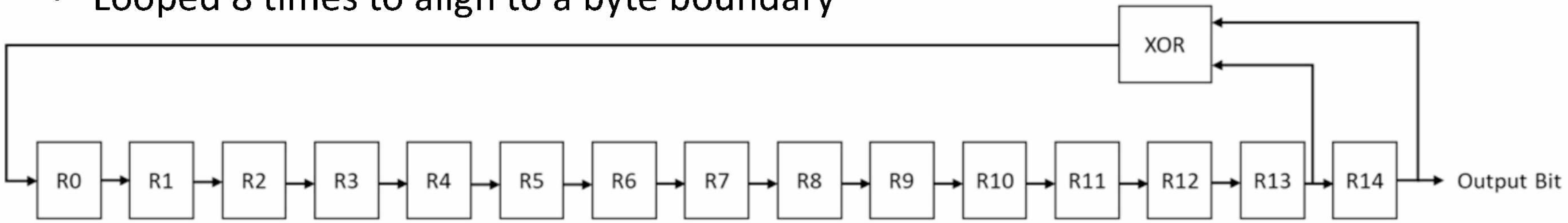
Testing

- GNU Radio had sample code for DVB-S2 (CCM only)



Testing

- Required data to be a data stream of MPEG-2 video packets
  - Developed script to have any data look like an MPEG-2 packet stream
  - Similar script required to convert it back to original data
- Did not work for NASA
  - Wanted input to be pseudorandom noise
    - PN 15 Code
      - Initialized to all 1s
      - Looped 8 times to align to a byte boundary



Pattern is 32767 bits in length.

Issues with GNU Radio

- NASA's DVB-S2 receiver does not work with MPEG-2 data streams
- Big Issues
  - A data rate of 15 Mbit/s is not achievable with GNU Radio
  - Changing the GNU Radio code or creating it from scratch would be significant
- A new approach is required
  - Matlab/Simulink HDL Coder and FPGA

Matlab/Simulink HDL Coder—Current Status and Next Steps

- Currently developed Matlab functions:
  - Baseband header insertion
  - Baseband scrambler
  - Outer BCH Coding
  - Inner LDPC Coding
  - Bit Interleaver
- Next steps
  - Verify current code compatibility with HDL coder
  - Physical layer header insertion, physical layer randomizer, modulation and filtering
  - Transfer SDR lead to the next person

Questions